Assesing Terra Disposal Orbit Candidates from an Orbital Debris Perspective

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The NASA Terra satellite is reaching the end of its mission life. Because the satellite resides in the 705 km Earth Science Constellation, disposal strategies need to be considered to remove it from this densely populated operational orbit. Of critical importance was the need to examine the future potential risk to other satellite residents of the 705 km constellation due to an unexpected breakup event of the Terra satellite post-disposal. This study quantifies the comparative risk of debris impacts associated with the two leading candidate disposal orbits (701 km vs. 686 km) and characterizes the suitability of each orbit for the purpose of long-term spacecraft disposal. The increase in collision risk to any member of the 705 km Earth Science Constellation is very modest. The long-term, average, total risk (including the ambient background risk) due to a Terra breakup at a disposal of -19 km (i.e., 686 km) relative to the 705 km constellation is 9.7×10^{-6} impacts/day versus 1.0×10^{-5} impacts/day for a disposal of only -4 km (i.e., 701 km). For perspective, note that the nominal space background risk to the 705 km constellation is 9.2×10^{-6} impacts/day which implies a very modest increase in risk (approximately 3% difference between the two cases) due to a Terra breakup in either disposal orbit.

I. Introduction

TERRA is a member of the 705 km Earth Science Constellation, which is made up of several active satellites that fly in a 705 km circular, sun-synchronous orbit at a 98° inclination. These satellites are spaced a few degrees apart in mean anomaly such that they are able to observe the same location on the ground at nearly the same time and sun-angle. This enables the science data gathered from each mission to correlate and complement one another. As a result, this area of space is very crowded (6-7 satellites shareing the same orbit), very valuable (from a science perspective), and very vulnerable to orbital debris (since multiple assets are in close proximity).

The 705 km Earth Science Constellation's Misson Operations Working Group (MOWG) typically meets twice a year to discuss upcoming maneuver plans and how to safely operate these active satellites in close proximity to each other. The governing document which contains the agreements made between the constellation members is called the "Constellation Operations Coordination Plan for the Morning and Afternoon Constellations." In the first version of this document[1] the constellation members agreed that in order for any mission to exit the constellation safely, the mission must lower its apogee at least 2 km below the lowest remaining member's perigee. Given the current set of constellation members, this meant that the exiting mission must lower its orbit below 692 km and have a resultant orbit approximately 19 km below the constellation's mean altitude. However, upon further analysis[2], it was determined that this safe exit approach was overly conservative. Engineers in the NASA Goddard Flight Dynamics group were able to show that the exiting mission maintains enough synchronization with the constellation orbits even

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as its eccentricity changes, such that a safe exit only needs to be approximately 4 km below the constellation envelope. Based on this analysis, the Constellation Operations Coordination Plan is being updated and coordinated with all constellation members.

Terra was launched prior to development of the NASA Procedural Requirements for Limiting Orbital Debris Generation (NPR 8715.6)[3], the latest revision in NASA's 15-year-old policy designed to curtail the growth of the orbital debris population. The NPR imposes orbital reentry requirements of 25 years from the end of the operational mission or 30 years from launch. Terra, having completed its Preliminary Design Review (PDR) prior to enactment of the current reentry NPR, was granted an exemption. With this exemption in place, Terra's end of mission plan has always been to fly until there is only enough fuel remaining to exit the constellation, and then at that time, perform the exit. This strategy has assumed that lowering the orbit by 19 km was the requirement for a safe exit and safe graveyard orbit. However given the new analysis[2], Terra is currently pursuing exiting the constellation according to a new requirement of 4 km, which would extend the mission's lifetime by allowing Terra to reserve less fuel for the constellation exit maneuvers. When this proposal was presented to the MOWG, there was concern as to the increased debris risk Terra might pose (should it unintentionally breakup) if it exits according to the new (4 km) approach and not do any further lowering after the science mission ends. Therefore, at NASA's request, the authors were contacted to perform the risk analysis between the two different resultant orbits of 19 km versus 4 km below the constellation envelope.

II. Problem Statement

Using The Aerospace Corporation's Debris Analysis Response Tool (DART), a Terra breakup event was simulated at altitudes of 19 km (686 km) and 4 km (701 km) below the 705 km Earth Science Constellation. This hypothetical breakup was modeled on 1 November 2014, such that actual Two-Line Element Sets (TLEs) from that date could be used to generate the orbits of the 705 km constellation members. The members of the 705 km Earth Science Constellation used in the simulation were: Aura, Aqua, Cloudsat, Calipso, GCOM W1, OCO-2, Landsat 7 and Landsat 8. Additionally, a grid of 1,296 fictitious satellites were also generated and evenly spaced around the Earth to assess the effect of relative geometry on risk. The intention of this grid is to identifiy the worst case relative geometry (between Terra and an Earth Science satellite) since orbital perturbations gradually change Terra's disposal orbit and an actual, real-world breakup time for Terra is not known *a priorri*.

To force a complete fragmentation of Terra from a collision and at the locations specified in the statement of work, a 5 kg object was artificially created to intersect the Terra orbit on its first revolution after midnight on 1 November 2014. The relative velocity of the collision was approximately 9 km/s which, experience has shown, is a median value for close approaches in LEO. However, the degree of fragmentation must also be selected, where 100% would be typical of a center-of-mass to center-of-mass collision and lesser values would be typical of an offset collision that results in partial fragmentation. Specifying a smaller fragmentation percentage has the effect of creating less debris overall, reducing the spreading velocities, and changing the mass distribution such that several larger, more massive remnants of the parent object remain intact. Most collisions will have some offset to the mass centers and will produce proportionally fewer fragments. For example, the Iridium-33 vs. Cosmos-2251 collision in 2009 was a partial fragmentation that was estimated[4,5] to be less than 20% by comparing the number of 10 cm and larger fragments predicted by the breakup models to the actual number of objects tracked and catalogued by the Space Surveillance Network. The remaining sections of this paper will discuss the following topics in more detail: DART breakup and risk model, hypervelocity collision physics, the fictious satellite grid, the parametric cases chosen, the resulting risk from these cases, the implications of this risk, and final thoughts and conclusions.

A. DART Process and Assumptions

DART is a suite of proprietary tools that are executed from a master interface. At the heart of the process are three applications developed and refined over at least two decades of usage. The program, particularly the debris propagation routine, is highly parallelized and can be executed on very large cluster computing resources. For this study we used a cluster with over 1500 cores.

The first application is the IMPACT model, a physics-based semi-empirical explosion and hypervelocity collision model[6]. Energy, mass, and momentum conservation are enforced, and it utilizes empirical fragment, velocity, and mass/size/area distributions. It also differentiates between different types of objects (booster, post-boost vehicle, satellite) and considers the densities and mass fraction of component materials. Inputs to IMPACT are mass information and the state vectors of the two colliding objects at the instant of collision. The output provides satistically-representitive discrete orbit element sets for each debris particle along with the size, mass, and spreading

velocity. IMPACT has been in use at Aerospace for nearly 20 years and has been cross-validated with MDA and NASA breakup models[7].

The second application is DEBRISPROP which propagates all of the fragments created by the IMPACT model using a semi-analytic, mean element method. It also accounts for atmospheric drag by using solar activity data together with the size and mass values from IMPACT. DEBRISPROP is designed to propagate an extremely large number of objects such as a debris field (as wel as the "protetcted satellites" of interest) at selectable levels of fidelity using parallel processing techniques and all available computer resources. The output is an ephemeris for each fragment that can then be used in a conjunction analysis.

The third DART component finds the points of closest approach with each fragment, and calculates the probabilities of collision. The user can select a scaled-cross-sectional-area risk computation or a covariance based methodology[8] where covariance is derived from the spreading velocities and propagated with the debris. Both methods have proven to provide comparable results. The collision probabilities are accumulated for each day and written to output files. An additional auxilliary component is comprised of a set of routines which summarize and present the results in tables and plots showing absolute and relative risk.

The cross-sectional area and background risk for each protected satellite are maintained in a database. The background risk for each member of the Earth Observation Constellation is different specifically because the "collision radius" for each satellite is different. Orbit and atmospheric data is downloaded and stored locally when an analysis is initiated. By storing a local copy, an analysis can be modified or run again while keeping raw data the same.

B. Hypervelocity Collisions

Hyper-velocity collisions, like the type that would most likely destroy Terra, do not behave dynamically like collisions with which we are familiar. Objects are moving faster than the shock waves can propagate through the structure. At the average collision velocity of 10 km/s, each parent object would appear to pass through the other before the shocks in the structures shatter them into fragments of varying sizes and mass. In the process, each fragment receives a small change in velocity (at least in relative terms) giving each fragment a boost in a slightly different direction. Very little momentum is transferred between the two colliding objects. Each debris fragment has a somewhat randomly distributed velocity relative to the parent center-of-mass that will cause the individual debris clouds to slowly expand and evolve over time, according to the laws of orbital motion, eventually becoming so widely distributed that the new population of space debris simply adds to the existing background. With tens of thousands of fragments 1 cm and larger produced by a typical on-orbit collision, the initial debris cloud expanding from the parent object looks like an explosion. After just

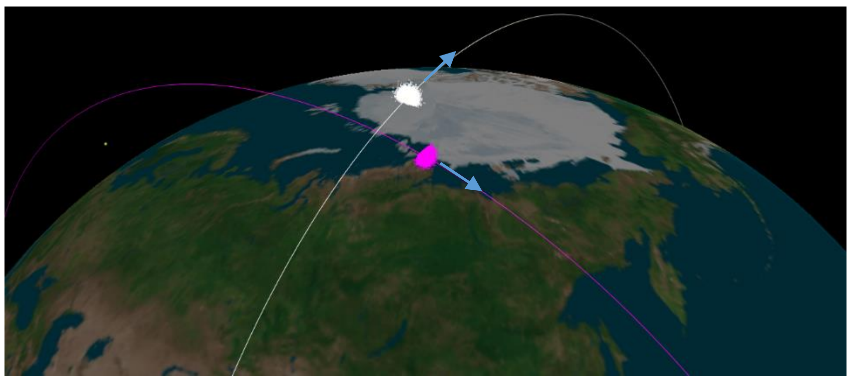

Figure 2. Two debris clouds formed shortly after a hypervelocity collision.

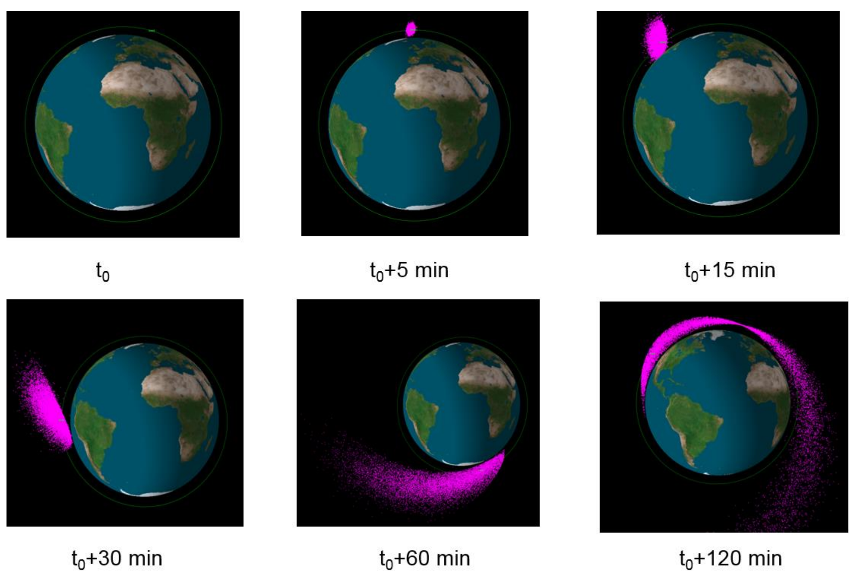

Figure 1. The evolution of a debris cloud from time of breakup, t_0.

one revolution, as shown in Figures 1 and 2, the debris cloud quickly expands into other altitudes. Although the debris is initially nearly coplanar with the parent orbit, differences in precession rates will cause the right ascensions of the ascending nodes to disperse as well.

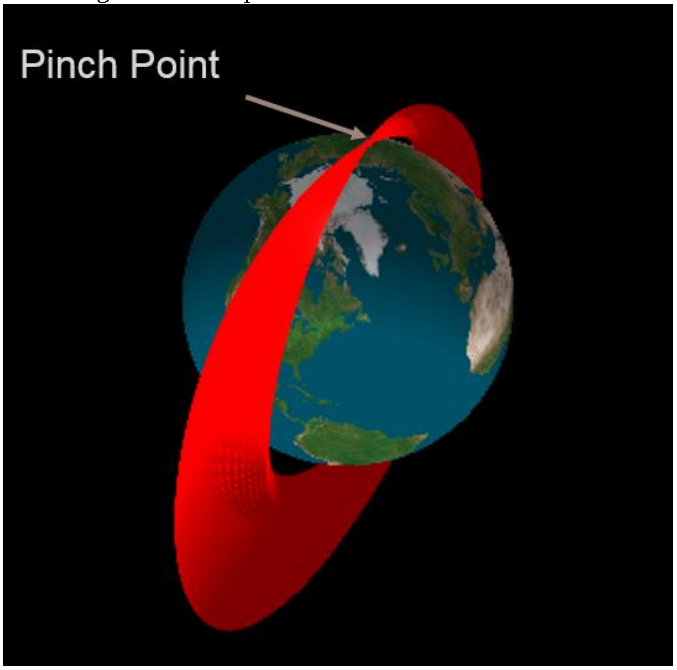

Figure 3. The "pinch point" of a debris cloud.

The risk to other protected satellites depends in part on the relative position of the collision with respect to the orbits of those satellties. Each debris fragment will nominally return to the location of the initial breakup. All of the fragments will appear to converge to this "pinch point." Figure 3 illustrates the pinch point as a collapsed region of the debris torus. Any spacecraft flying through the cloud near this pinch point will have a signifigantly elevated collision probability because the local density of debris is much higher here than for any other part of the debris cloud. The pinch point can persist for many months until the orbital perturbations cause the debris orbits to spread in right ascension, among other effects.

C. Relative Geometry Satellite Grid

Varying geometry of the collision location relative to the 705 km Earth Science Constellation will affect the risk. To properly bound the risk, we could run hundreds of cases by varying the the location of the collision. However, generating and propagating numerous debris clouds would be an extremely lengthy process. An equally effective approach is to propagate only a few debris clouds, and represent the varying relative geometry by populating a 705 km, circular, sun-synchronous constellation with a large number of satellites spread in right ascension and mean anomaly (as is done in this paper). The large number of debris fragments are propagated only once, as are the grid objects, and the resulting risk analyses will provide upper and lower bounds of risk from a Terra fragmentation in either of the proposed Terra disposal orbits.

For this project, we set the right ascension and mean anomaly spacing to 10° giving a total of 36 satellites in each of 36 planes with a total of 1,296 satellites comprising the grid as shown in Figure 4. The worst case example from the grid risk analyses identifies the "wrong-place, wrong-time" orbit where the short term risk is at a maximum. If Terra drifted such that the relative geometry of its orbit matched the worst case grid geometry, the risk to the Earth Science Constellation from a Terra fragmentation event would at its highest. This case is plotted as dots in Figures 14-21 in Appendix B.

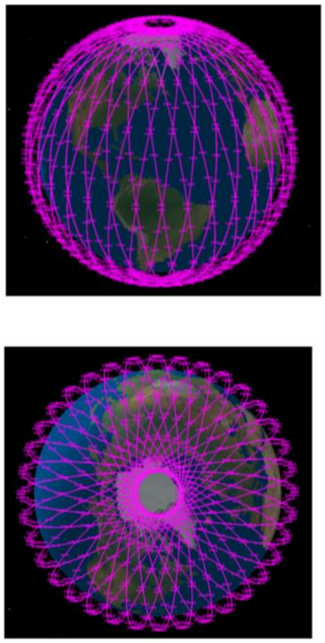

Figure 4. Grid of 1,296 fictitious satellites used to address "wrong place, wrong time" risks.

D. Parametric Study

As indicated in Section II B, the location of the pinch point matters as well. For sun-synchronous orbits, the two most critical locations would be a fragmentation near one of the Earth's poles (where all of the orbits would converge near the pinch point) and at the equator (which reduces the debris density at the poles). With two different disposal altitudes, two collision locations, and considering two different fragmentation levels (100% and 10%), eight separate cases were constructed.

III. Risk to the 705 km Earth Observing Constellation from a Hypothetical Terra Breakup

Risk of collision with Terra debris for each member of the 705 km Earth Observing Constellation is presented over a 30 day span for all eight cases. For each spacecraft in Figures 6-13 (Appendix A), the probability of collision is shown in two separate plots that are displayed side-by-side for ease of comparison. Each plot displays results for one Terra disposal orbit: the 19 km lower orbit on the left and the 4 km lower orbit on the right. Four series in each plot represent the four distinct breakup and risk analyses conducted for that spacecraft and Terra disposal orbit (i.e., polar and equatorial fragmentation events with 100% and 10% fragmentation). The pre-Terra-breakup background risk is also included as a dashed horizontal line for comparison.

Risk calculations are based upon the 1 cm and larger debris fragments created by the collision of Terra with another object. It was assumed that the colliding object was large enough to completely fragment Terra, but too small to create a its own debris cloud. As a general rule of thumb, impact with a particle 1 cm or larger is lethal to a satellite, whereas impact with a particle in the millimeter size range may cause localized damage but may not necessarily disable a satellite. It is the objects between 1 cm and 10 cm that dominate the risk to any mission. The majority of the debris in this size category cannot currently be tracked, produces major to catastrophic damage in a collision, and creates a persistant daily risk to satellites. The risk from these smaller particles can only be treated in a statistical sense because there are few or no discrete orbits established for objects in this size category. Therefore, the risk results for this study are computed from the 1 cm and larger fragments resulting from a catastrophic breakup of Terra due to a collision with a small space debris object.

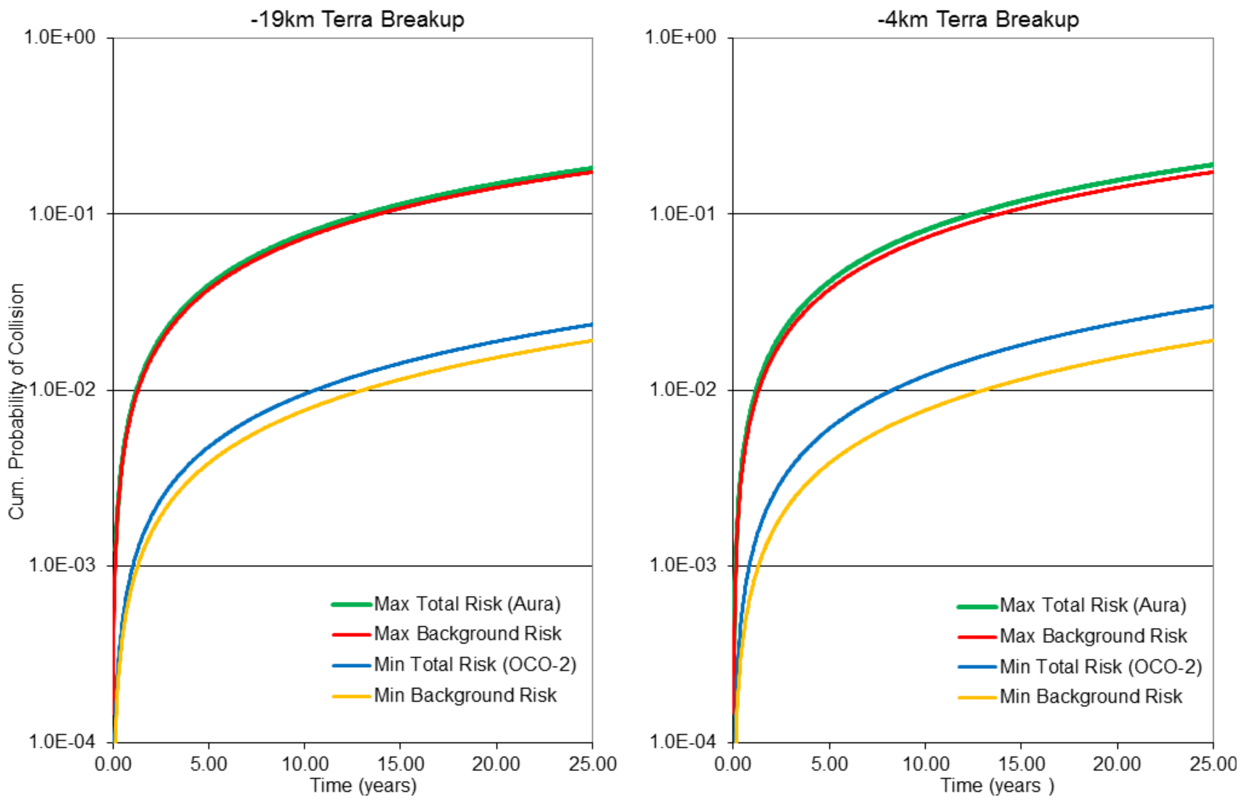

Figure 5. Cumulative Risk to Aura (maximum risk satellite) and OCO-2 (minimum risk satellite).

Terra, of course, is not the only object that could pose a risk to the 705 km Earth Observing Constellation if it were to collide with another object. There are currently 772 other objects with a cross sectional area greater than 12.6 square meters or a radius larger than 2 meters that cross through altitudes of 685 to 725 km. Approximately 103 of these objects are in near circular orbits such that they remain within the altitude band of the Earth Observing Constellation for most if not all of their orbit. For comparison then, there are already 103 Terra-sized objects near enough to the 705 km constellation to create a risk similar to the results reported in this study.

In only a few cases does the risk incurred from a Terra fragmentation approach or exceed the background risk. There are some very interesting results for certain members of the constellation. Referring to Figures 9, 11, and 12 (Calipso, OCO-2, and Landsat 7), the equatorial breakup in the 4 km disposal orbit creates a higher and more persistent

risk than any other case. A similar result appears in Figure 13 for Landsat 8, but the 100% fragmentation is the only case where the associated risk is comparable to the background risk.

Our experience in using DART to model on-orbit collisions and breakups has shown that the risk will most often drop considerably during the first month after an event. Long-term probability of collision, i.e., after 30 days, is usually a fraction of the background risk and the plots for each satellite generally bear this out. However, each case is different, and generalizations about space debris and collision risk often have glaring exceptions. Nevertheless, an analysis of the results shows that the long-term risk is "generally" an order of magnitude lower than the background risk for the 19 km disposal orbit. There are a few members of the constellation that will see a risk approximately equal to the background risk for the 4 km disposal orbit; however, this means only that the "new" background risk has doubled. In no cases, other than a few transient spikes for a few days duration, will the risk be an order of magnitude higher.

As the debris cloud spreads and becomes more widely distributed it is best modeled as a new contribution to the background based on the long-term probability of collision calculated after 30 days (albeit a slight overestimate of risk since effects such as atmospheric drag are ignoored). The new daily risk may have doubled, for example, such as when the added risk from a Terra breakup is approximately equal to the background, but the effect over the long term, i.e., the cumulative risk, does not necessarily double. Using Aura and OCO-2 as examples because Aura has the highest overall risk and OCO-2 has the lowest, we calculate the cumulative risk over 25 years using the current background risk and then again using the increased risk that includes background plus the contribution from a Terra 100% fragmentation. The results are shown in Figure 5, using the same layout where the plot for the 19 km disposal orbit is on the left and the results for the 4 km disposal orbit are on the right. The upper curve (blue for OCO-2 and green for Aura) represents the total risk (Terra debris + pre-breakup background) and the lower curve (yellow for OCO-2 and red for Aura) represents the original, pre-breakup background. The cumulative risk curve for all remaining spacecraft of the 705 km Earth Science Constellation will lie between these two extremes but are not shown for clarity. The plots show a relatively modest difference between the 19 km and 4 km disposal orbit candidates that generally does not exceed 10-20% and is much smaller than the difference in the range of the two spacecrafts' risk curves.

The daily risk curves illustrated in Figures 6 through 13 of Appendix A indicate a small difference between the -19 km and the -4 km disposal orbits. Summarizing data contained within Figures 6 to 13 for the entire constellation shows to some extent the shared risk to each member of the constellation. A particular vehicle may have a lower risk for no other reason than its smaller size, but the higher risk to one of its neighbors is also an important consideration to its own mission. The constellation risk, separated into short-term (transient), and longer-term over the 30 day period and averaged over all spacecraft in the constellation is summarized in Table 1. Separated again by the different disposal orbits, maximum transient risk is defined as the maximum daily risk of the average of the four cases displayed in Figures 6 through 13 and generally occurs during the first 15 days following a breakup event when the debris cloud is very concentrated. Keep in mind that this is a maximum risk value and likely over-estimates the typical risk a member of the constellation will see. Conversely, the long-term risk represents the average of the four trails near the end of the 30 day plot. This corresponds to a time when the debris cloud has sufficiently dispersed to a level that can be considered part of the new background risk (new background risk = old background + long-term risk). The values reported in Table 1 originate from a statistical sample that includes all of the risk curves from all eight of the Earth Observation Constellation spacecraft. Looking at the average long-term risk, in Table 1, for example, the 4 km disposal orbit has a negligible increase in collision risk compared with the 19 km orbit.

Table 1. Transient and long-term risk averaged over 8 spacecraft (impacts /day).

	Metric	19 km Orbit	4 km Orbit
Long Term Risk	Minimum	2.6E-6	3.3E-6
	Maximum	22.0E-6	22.0E-6
	Average	9.7E-6	10.0E-6
Transient Risk	Minimum	7.0E-6	18.0E-6
	Maximum	28.0E-6	36.0E-6
	Average	15.0E-6	24.0E-6
Typical background risk =	10.0E-06		

IV. Debris Cloud Size and Lifetime

The number and size of debris generated by the Terra breakup events modeled in this study vary by up to 20% depending on the case. Table 2 summarizes the fragmentation data. At these altitudes, the lifetime of debris objects is heavily influenced by the spatial distribution of the debris cloud. Figure 22 displays the spatial density of debris

over a 60 day period following a Terra breakup. As indicated by the green band, the majority of debris remains in a 630 to 710 km band with very little decrease in average density over the 60 day window; i.e., the debris decays very slowly and is long lived. The Gabbard plot in Figure 23 shows the distribution of orbits resulting from the fragmentation: altitude vs. period with apogee and perigee plotted for each fragment The highest apogee altitude of any particle is over 3,500 km (perigee remains near 705 km) which corresponds to a lifetime of several hundred years. Conversely, some fragments are directed into an orbit with a perigee so low that they reenter either immediately or within a few revolutions. Figure 24 demonstrates this concept further by plotting the number of fragments (red curve) and fragment mass (blue curve) as a function of time over a 60 day window. Notice how debris mass is abruptly lost within the first few days and then slowly settles to a non-zero, long-term equilibrium as indicated by a near constant fragment mass in Figure 24.

Table 2. Number of debris fragments produced per breakup event.

Case Description	100%	10%
Terra 19 km, Polar Breakup	216,028	38,928
Terra 4 km, Polar Breakup	264,466	46,370
Terra 19 km, Equatorial Breakup	176,068	32,958
Terra 4 km, Equatorial Breakup	172,892	32,442
Mean	207,364	37,675
Std. Deviation	21%	17%

The lifetime of the various debris objects generated by an unexpected breakup of the Terra spacecraft is very difficult to calculate due to the sheer number of objects, large uncertainties in each object's drag coefficient, and the unknown synchronization between the breakup event and the solar cycle (which is the primary driver of upper atmospheric density). Generally, debris persisting during a solar minimum will have a longer lifetime compaired to that during a solar maximum and absolute (but not relative) risk may likewise change in response to the orbit lifetimes. Assuming a 65 kg/m^2 ballistic coefficient, representing a mean value for the constellation members, orbits in the range of 630 to 710 km will have a lifetime between 20 and 60 years according to reentry prediction charts[9]. During the breakup event about 50% of the debris will gain orbital energy while 50% will lose orbital energy. Therefore, for a given drag coefficient, about half of the debris objects will have lifetimes shorter than 40 years and half would have lifetimes longer with a few having lifetimes that last hundreds of years.

V. Conclusion

While any breakup event in LEO is highly undesirable, the difference in risk to the Earth Science Constellation between lowering Terra's orbit by either 19 km or 4 km is small (about 3% different), although the lower orbit (19 km) is marginally better. Both long-term and transient risk of the 4 km disposal orbit, though slightly higher, are very similar to the 19 km case. Both options roughly correspond to a long-term doubling of the pre-breakup background risk because the additional collision risk from Terra debris is roughly equal to the pre-breakup background risk. The story in terms of debris lifetime and distribution is even less differentiated since the range in altitude of the debris objects (up to 3500 km) is very large compared to the difference (15 km) between the two candidate disposal orbits themselves. Therefore the risk difference between the two disposal orbit candidates is statistically insignificant and may be treated as essentially the same.

Acknowledgments

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Appendix A

Daily risk plots for the 19 km and 4 km orbit lowering cases.

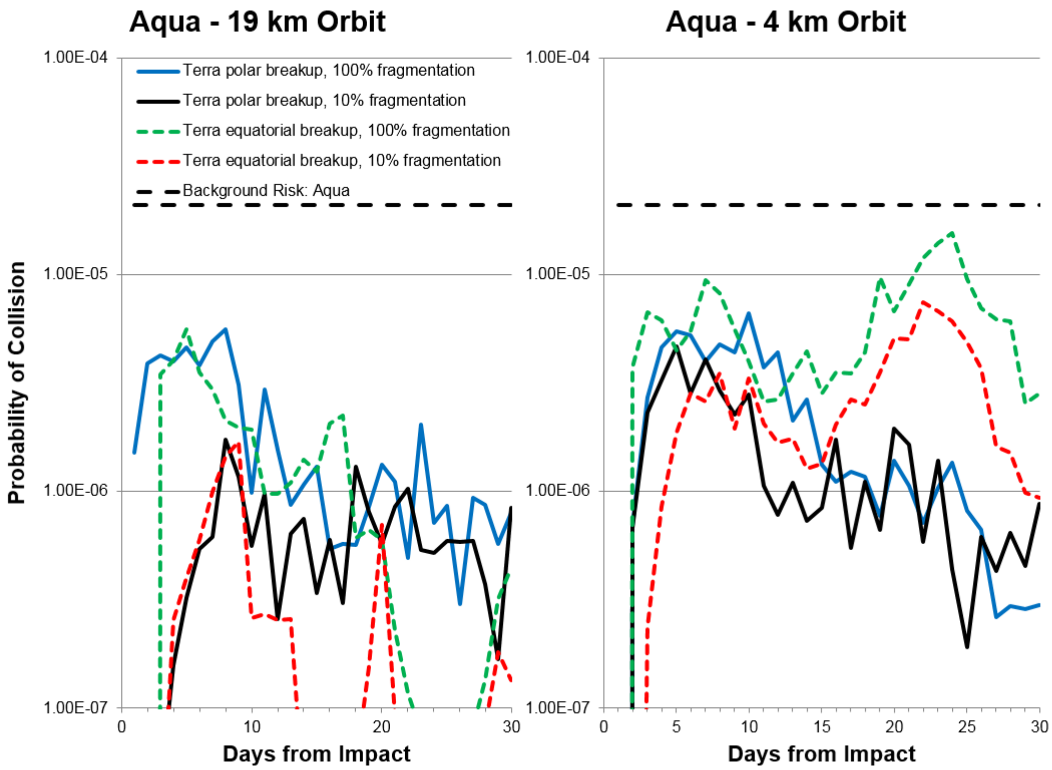

Figure 6. Aqua Collision Risk.

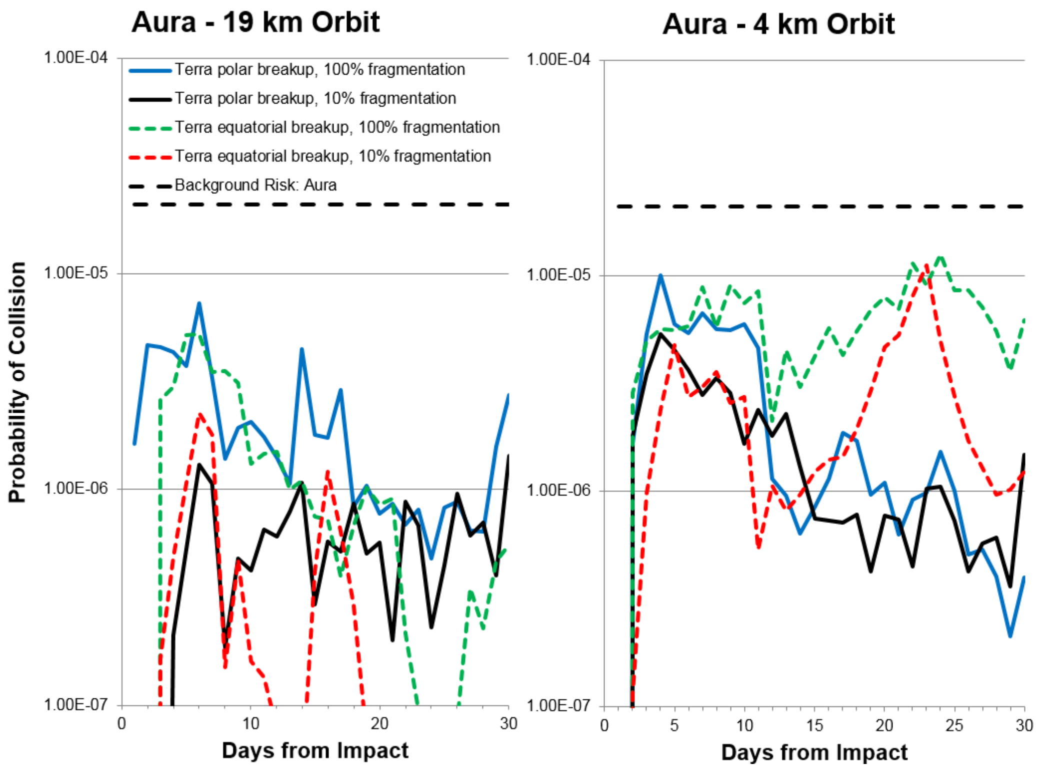

Figure 7. Aura Collision Risk.

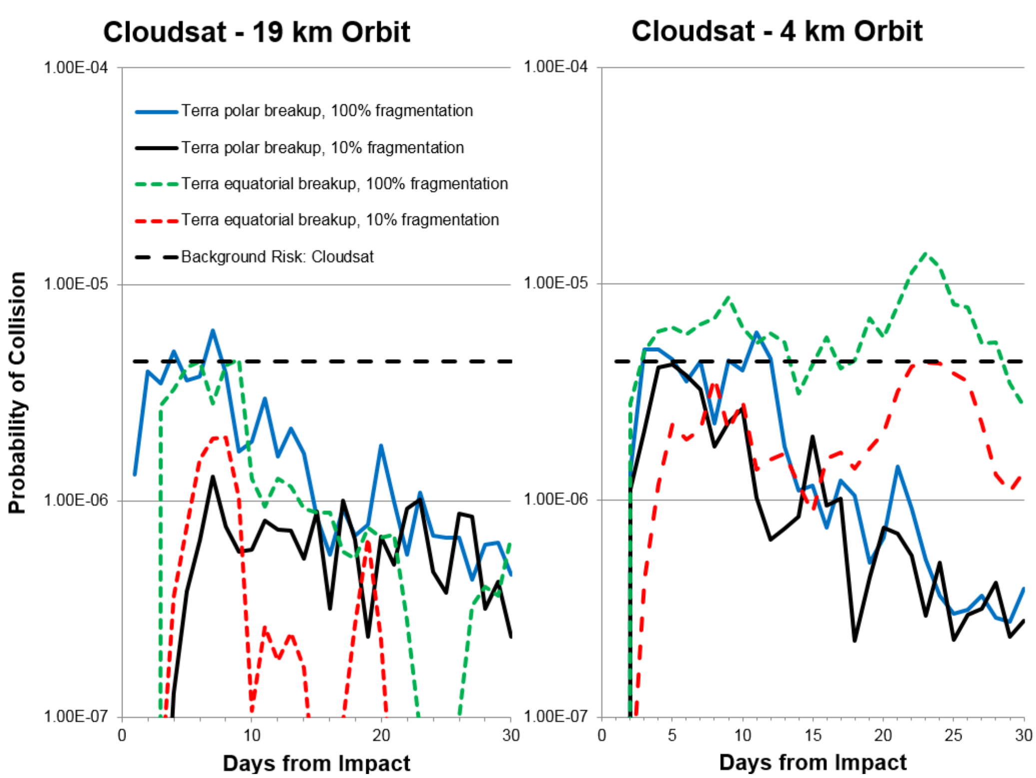

Figure 8. Cloudsat Collision Risk.

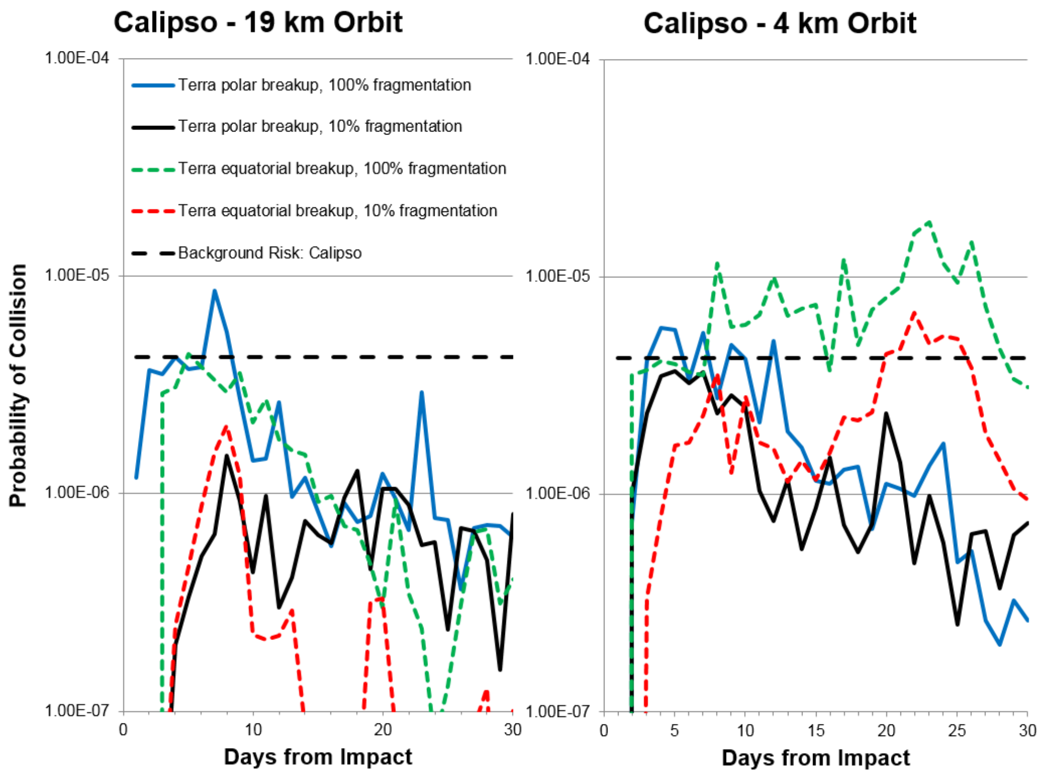

Figure 9. Calipso Collision Risk.

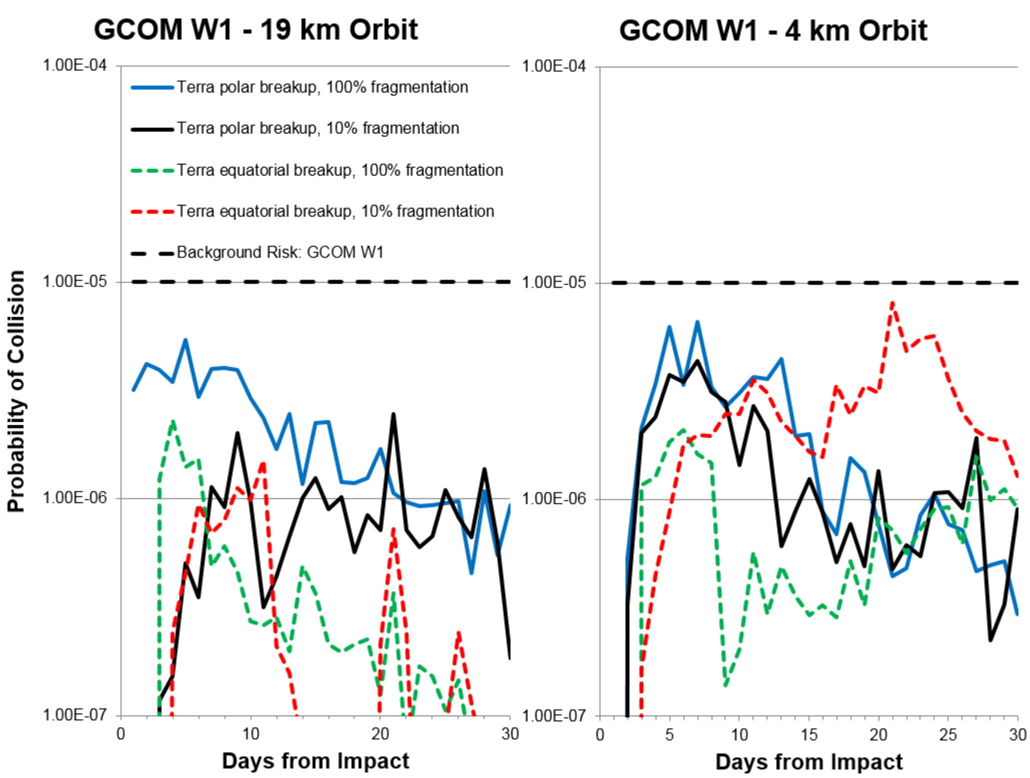

Figure 10. GCOM W1 Collision Risk.

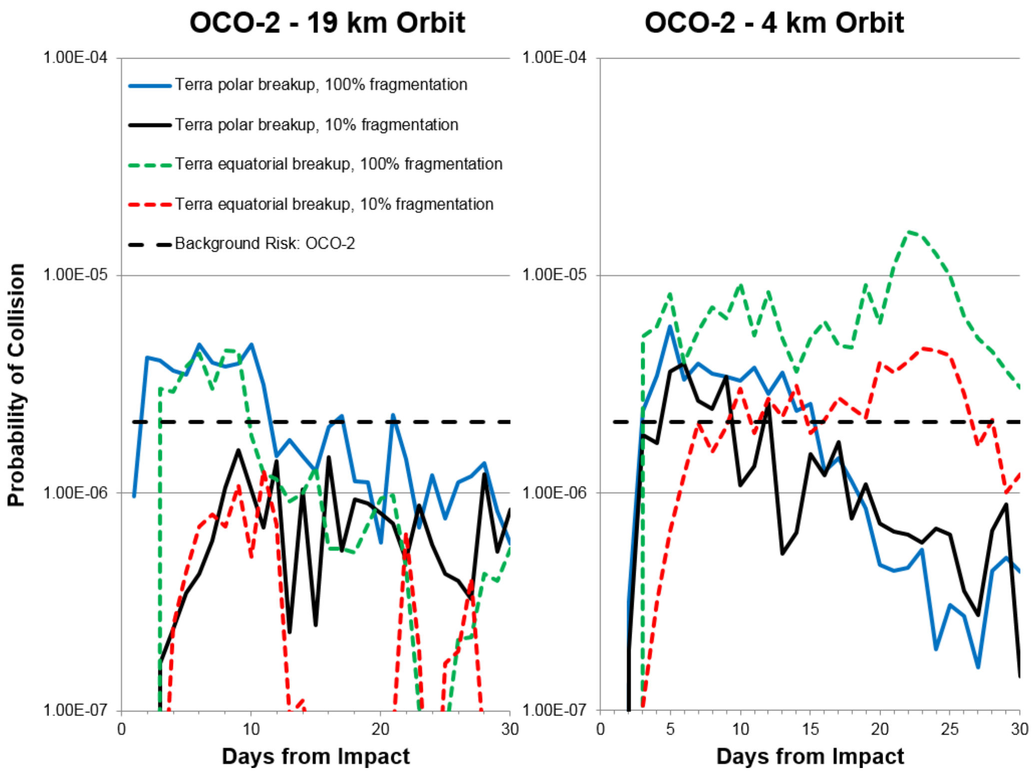

Figure 11. OCO-2 Collision Risk.

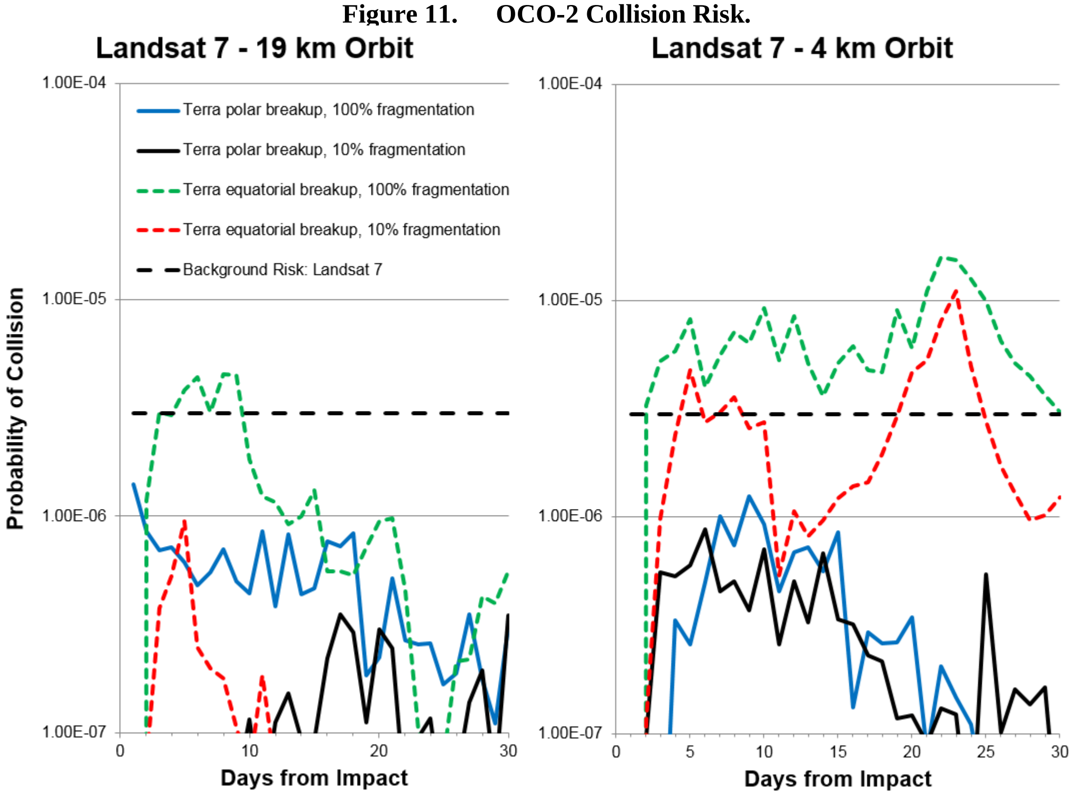

Figure 12. Landsat 7 Collision Risk.

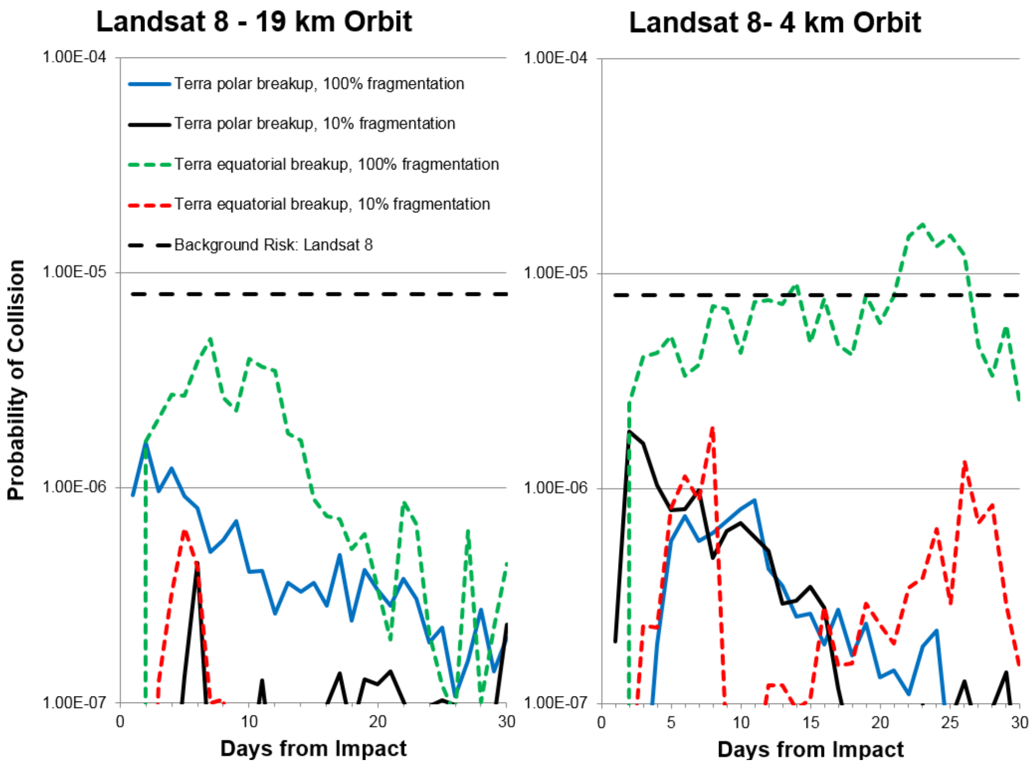

Figure 13. Landsat 8 Collision Risk.

Appendix B

Figures 14 – 21 show the probability of collision for all members of the 705 km Earth Science Constellation on one plot. Each plot therefore represents one of the eight cases as indicated in the title. Minimum and maximum pre-breakup background risk is also plotted for comparison. Finally, a series represented by points rather than a line indicates the maximum probability of collision for the grid of satellites. Each point in the series is the maximum risk (i.e., worst case) on that day to any of the 1,296 grid objects. Note that this may be a different object from one day to the next but the total number of objects represented in the series is normally less than a dozen. These maximum grid objects represent the "worst of the worst" orbits with respect to the Terra fragmentation and are usually represented by the grid object that passes through the pinch point at the time that the highest density of debris also converges to the pinch point.

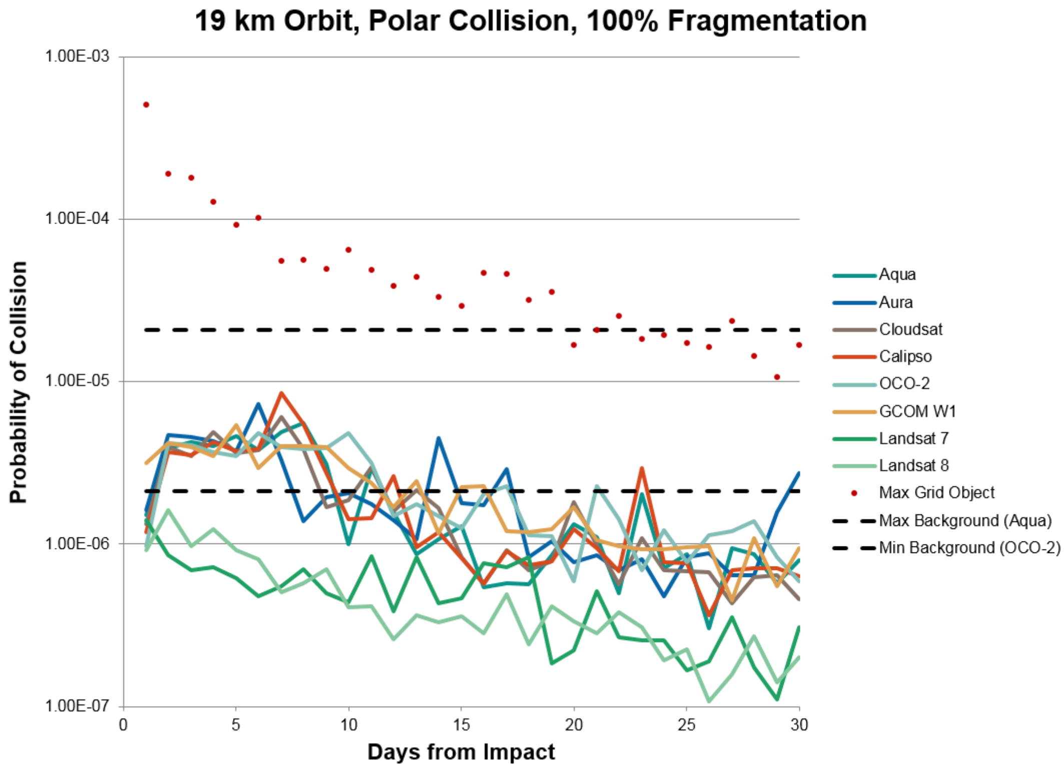

Figure 14. 19 km Lower Orbit, Polar Collision, 100% Fragmentation.

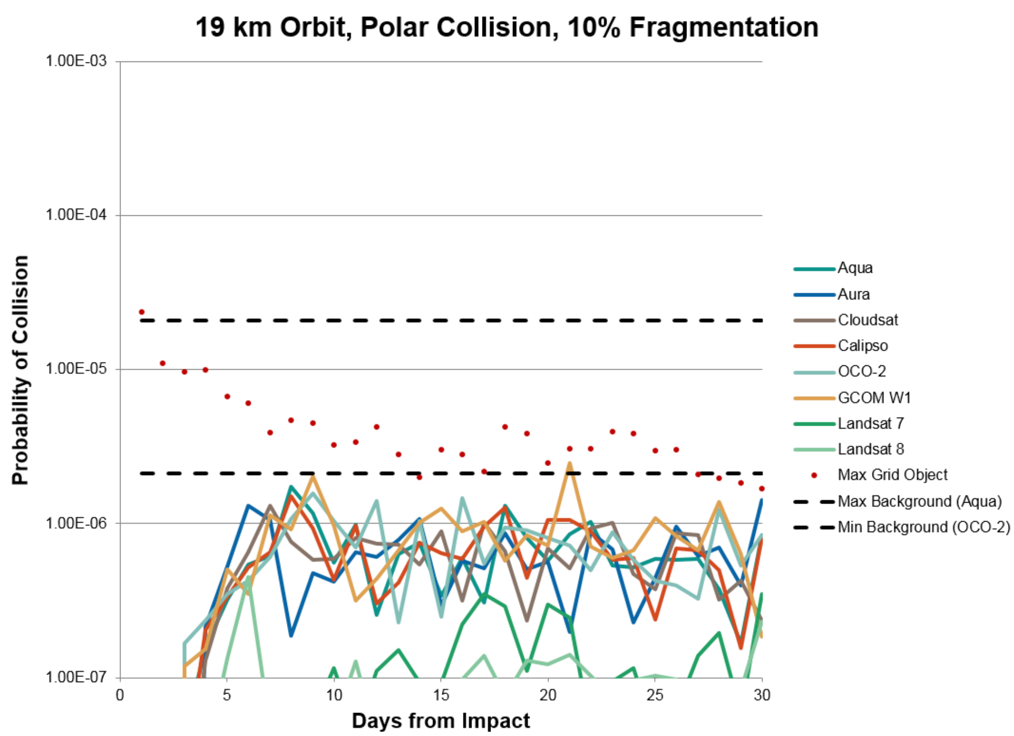

Figure 15. 19 km Lower Orbit, Polar Collision, 10% Fragmentation.

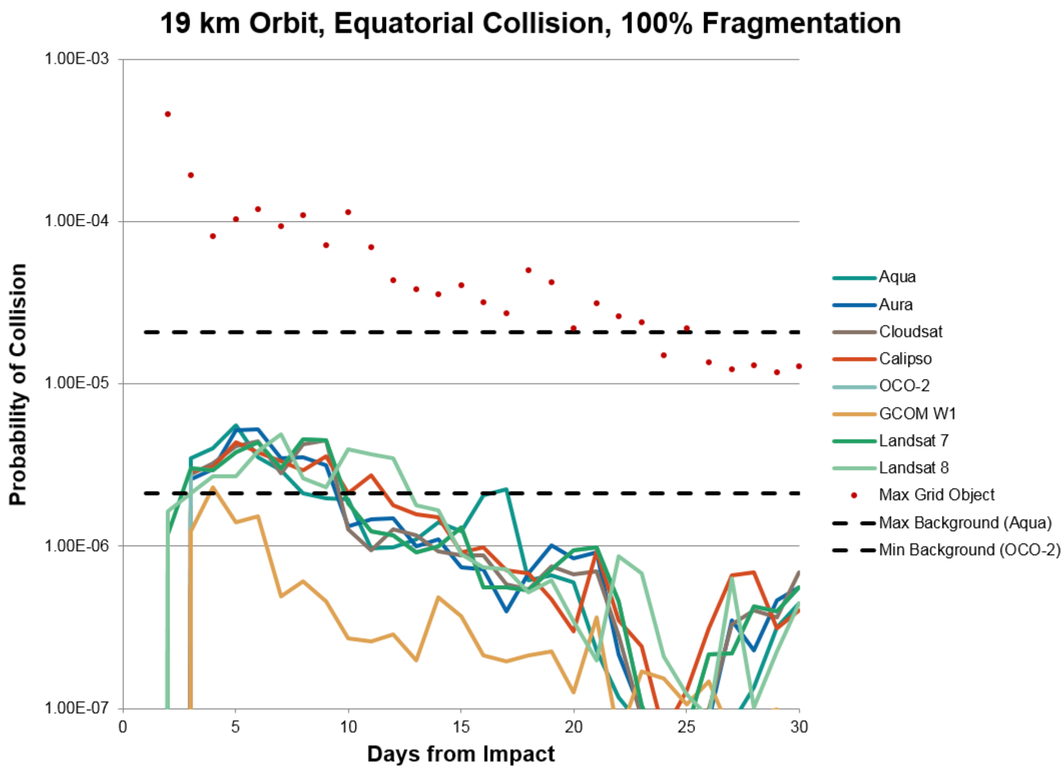

Figure 16. 19 km Lower Orbit, Equatorial Collision, 100% Fragmentation.

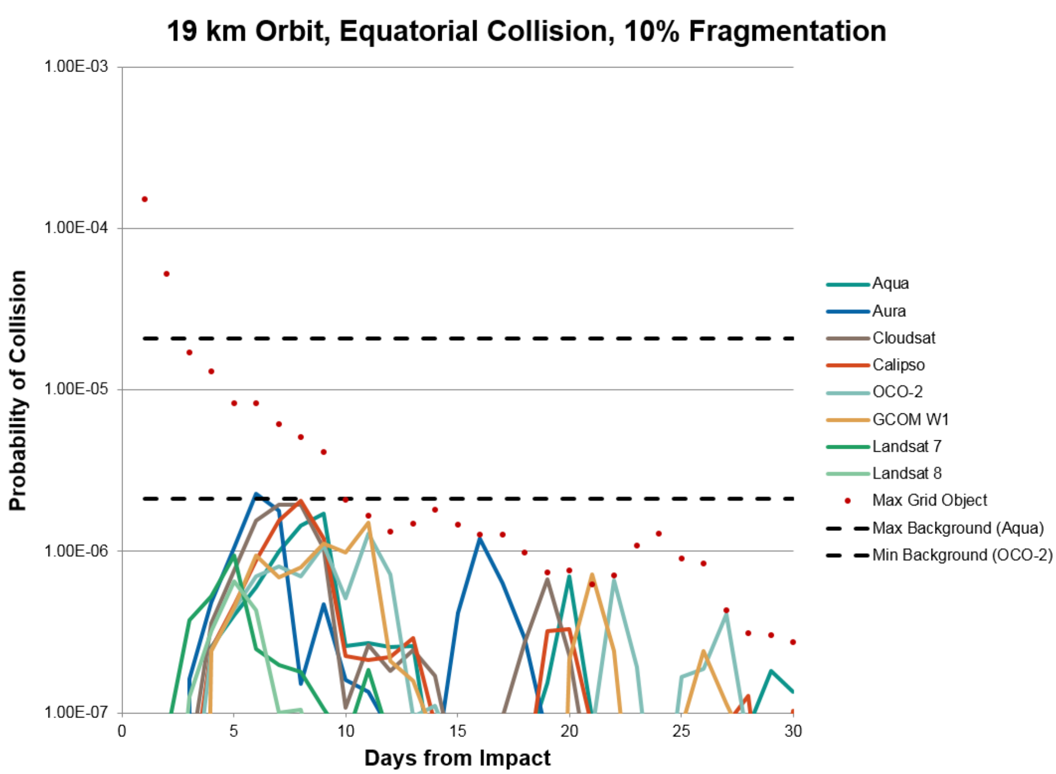

Figure 17. 19 km Lower Orbit, Equatorial Collision, 10% Fragmentation.

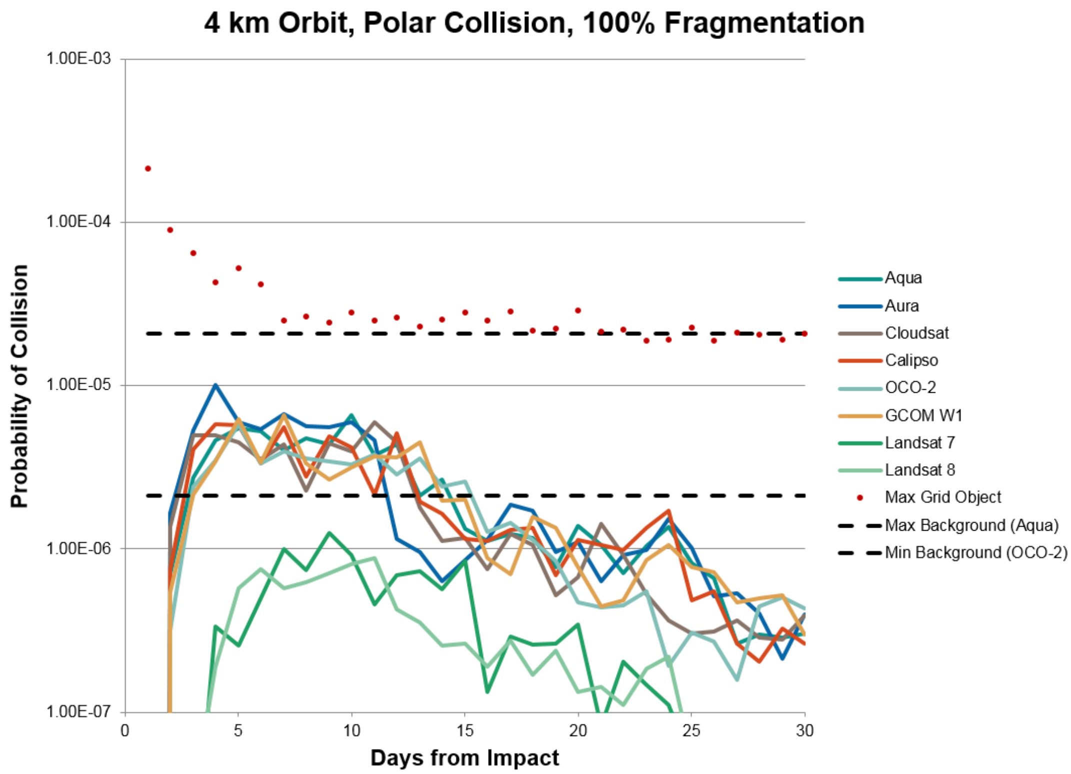

Figure 18. 4 km Lower Orbit, Polar Collision, 100% Fragmentation.

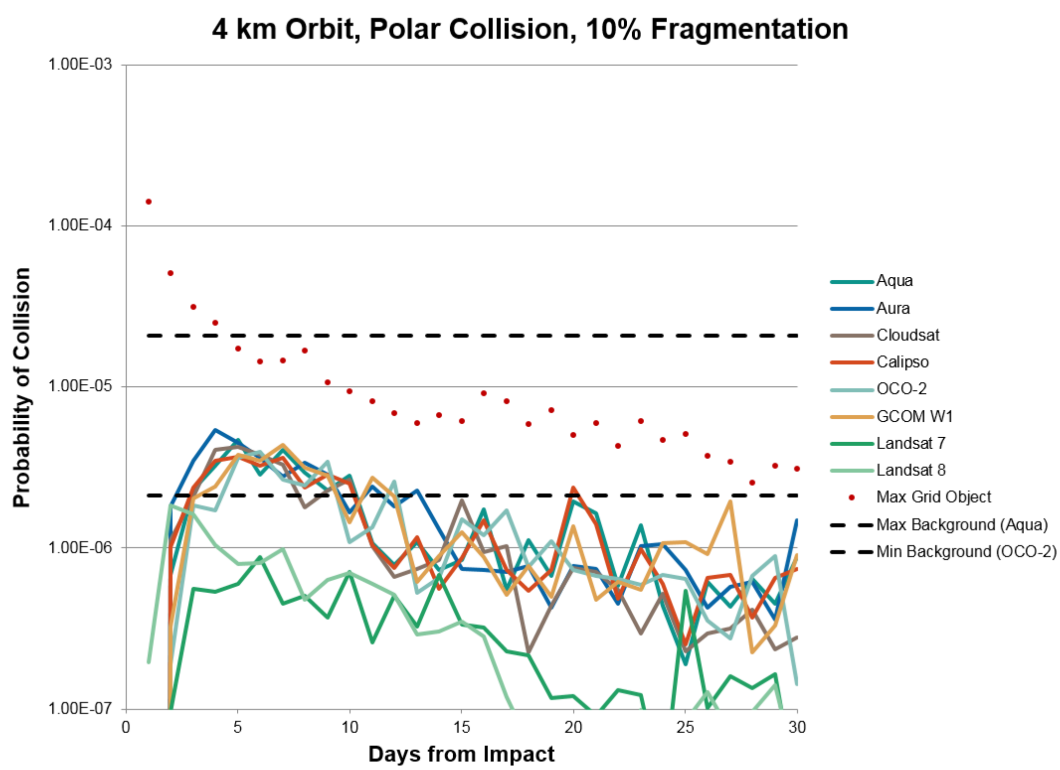

Figure 19. 4 km Lower Orbit, Polar Collision, 10% Fragmentation.

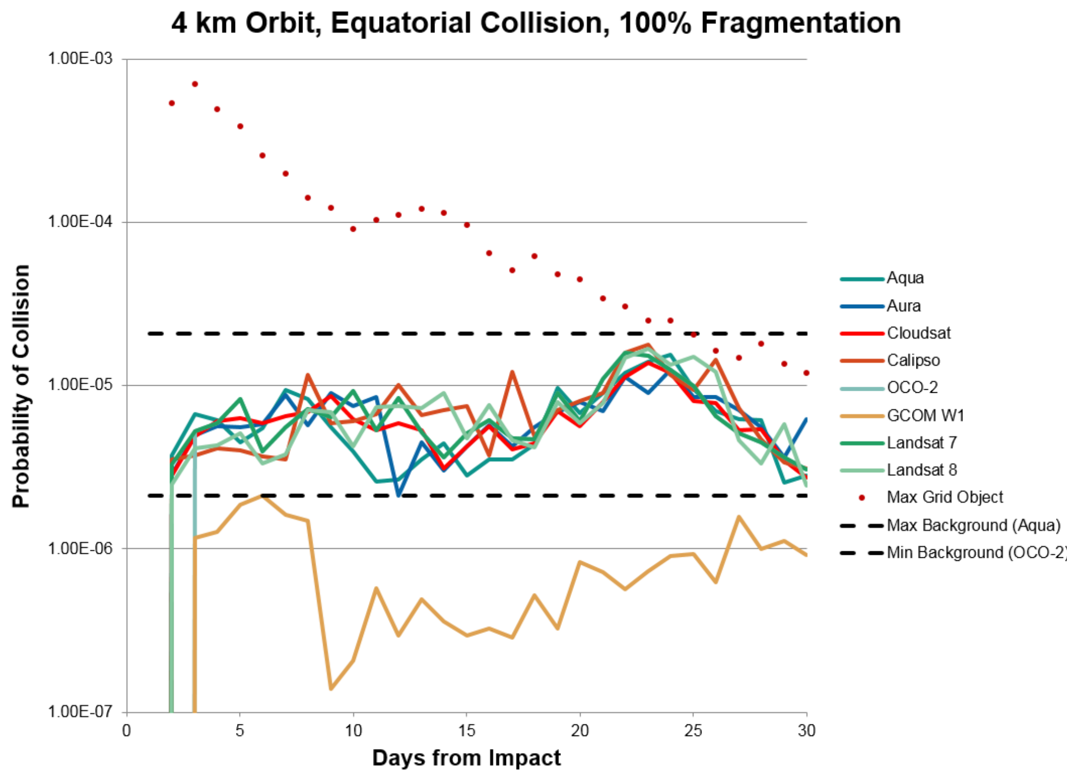

Figure 20. 4 km Lower Orbit, Equatorial Collision, 100% Fragmentation.

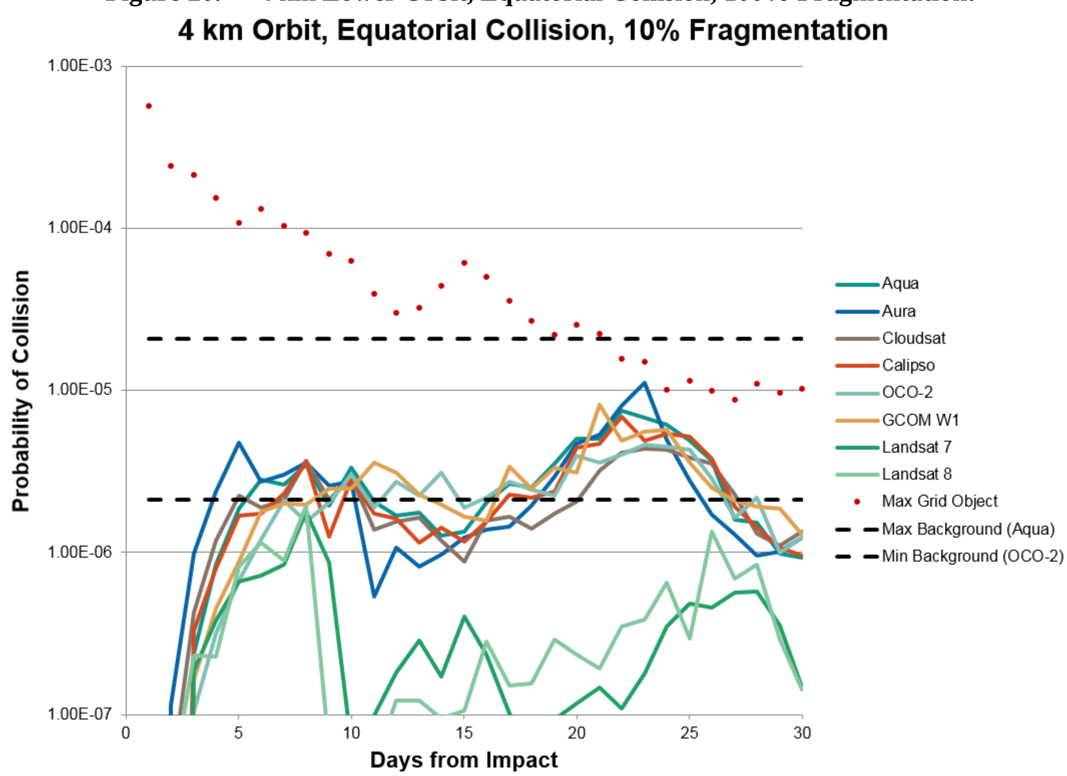

Figure 21. 4 km Lower Orbit, Equatorial Collision, 10% Fragmentation.

Appendix C

The following are supporting figures which describe hypothetical post breakup conditions of the Terra spacecraft.

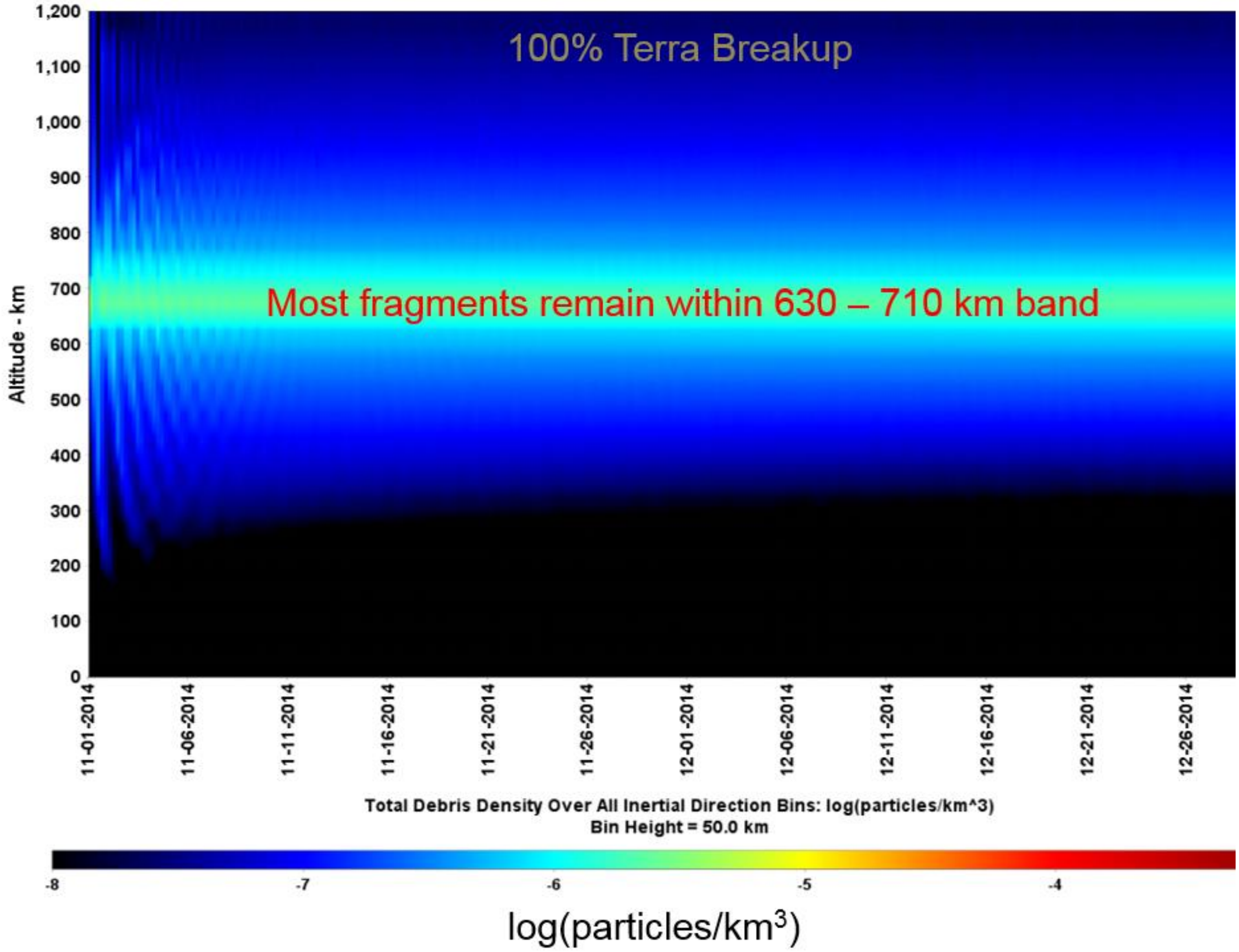

Figure 22. Spatial distribution of Terra debris over a 60-day, post breakup window.

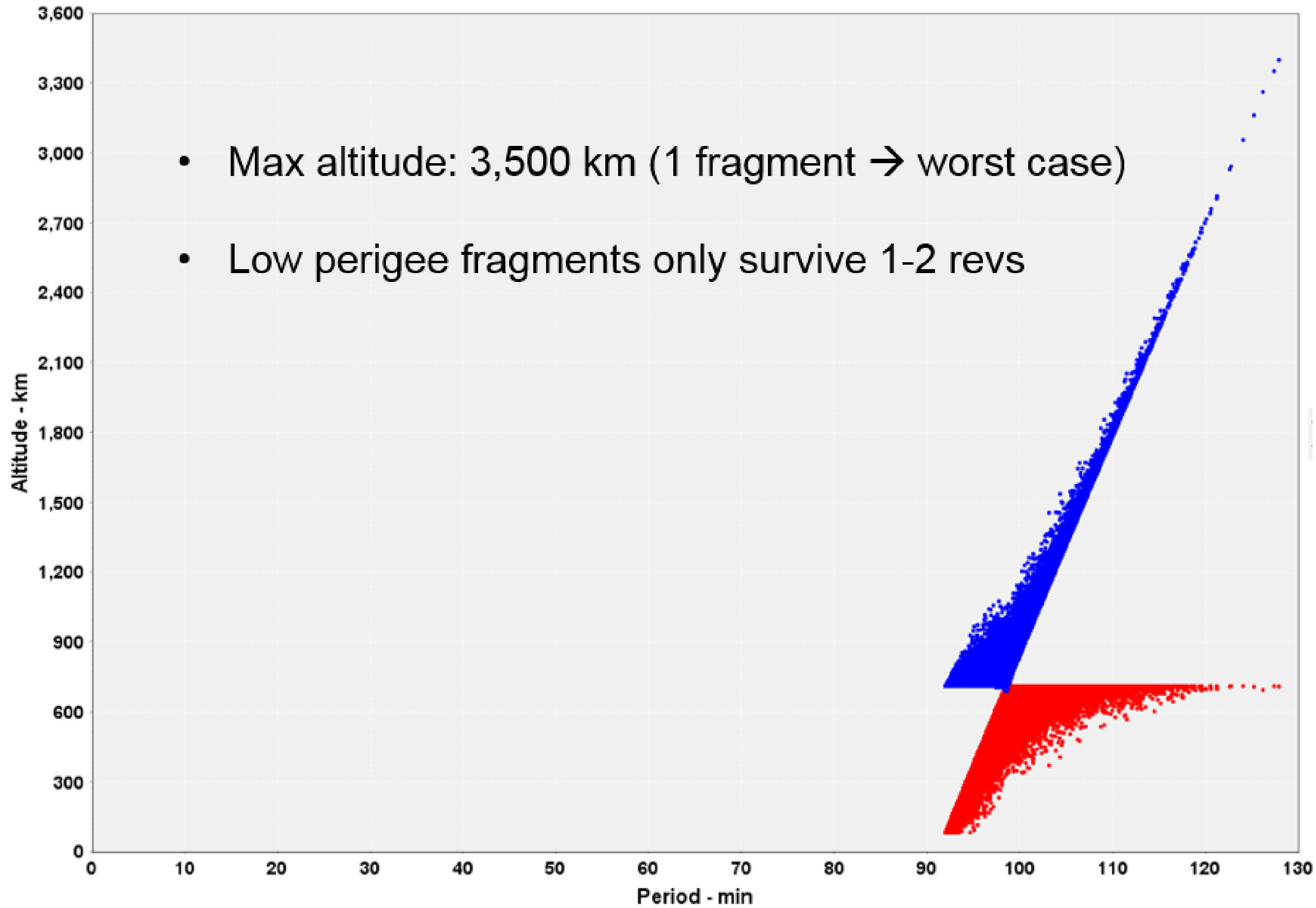

Figure 233. Gabbard plot of individual debris object's apogee (blue) and perigee (red).

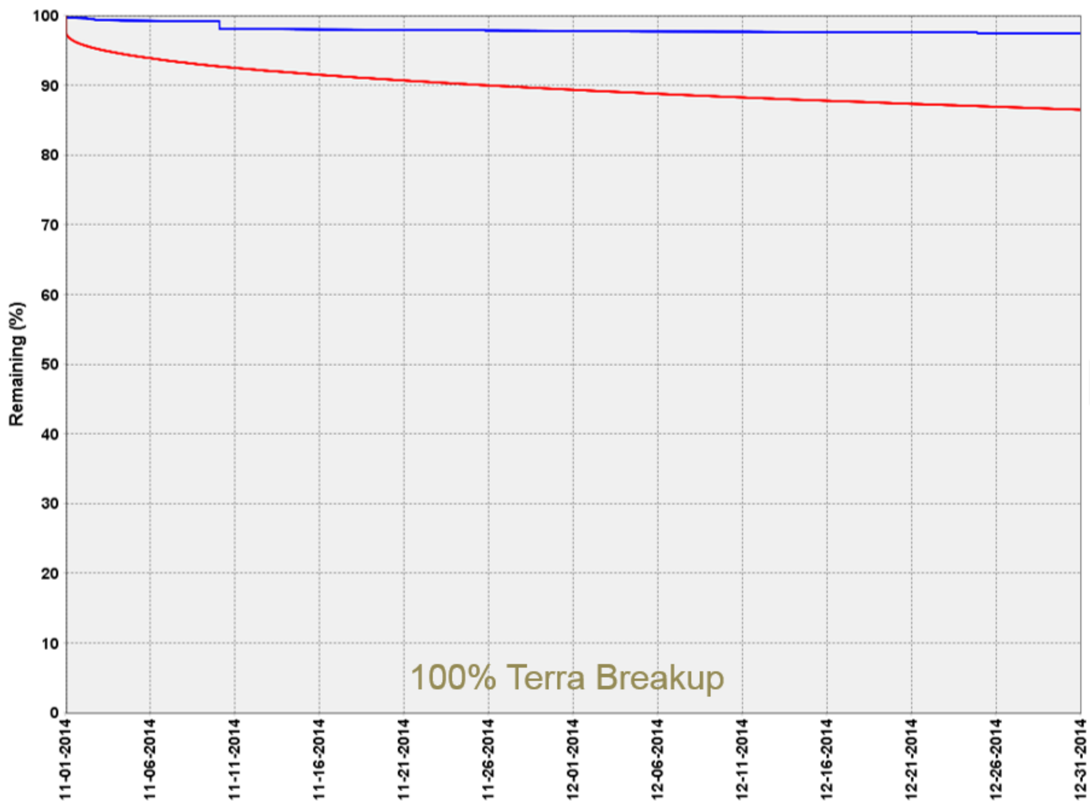

Figure 24. 60 day decay of Terra breakup debris by fragment count (red) and mass (blue).

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